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BREAKING BARRIERS TO THE FUTURE: EXPLORING USE OF BURGEONING COMMERCIAL SATELLITE TECHNOLOGY TO ENABLE COAST GUARD OPERATIONS IN THE RESOURCE-RICH ARCTIC

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December 2020

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Over the last 10 years the melt of the polar ice caps has opened access to a region of the Earth full of untapped resources. This has provided new economic opportunities for polar nations such as Canada, Russia, the United States, and Norway. Additionally, world powers such as China look to leverage more readily available shipping routes to reduce costs and further aid their economic expansion. The United States Coast Guard is charged with upholding peace and facilitating safe navigation in the region, but has been significantly hampered by a lack of capable assets. The service currently has one operational heavy icebreaker built in the 1960s and a medium icebreaker. A recent contract was awarded to VT Halter Marine to build up to six new icebreakers to aid the service in its polar missions. The current satellite communications being leveraged by major assets in the Coast Guard will not facilitate optimal operations in the Arctic, given the service's dependence on geosynchronous satellite constellations for internet connectivity. Emerging technologies can be leveraged to bridge this gap and ensure continued success in this frontier. This paper will provide a model to assist the Coast Guard in making future source-selection analyses of commercial communications satellite systems capable of providing service in the polar regions. This model was developed using techniques designed for multi-objective decision-making (MODM) and can be tailored to future organizational needs.

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ABSTRACT

Over the last 10 years the melt of the polar ice caps has opened access to a region of the Earth full of untapped resources. This has provided new economic opportunities for polar nations such as Canada, Russia, the United States, and Norway. Additionally, world powers such as China look to leverage more readily available shipping routes to reduce costs and further aid their economic expansion. The United States Coast Guard is charged with upholding peace and facilitating safe navigation in the region, but has been significantly hampered by a lack of capable assets. The service currently has one operational heavy icebreaker built in the 1960s and a medium icebreaker. A recent contract was awarded to VT Halter Marine to build up to six new icebreakers to aid the service in its polar missions. The current satellite communications being leveraged by major assets in the Coast Guard will not facilitate optimal operations in the Arctic, given the service's dependence on geosynchronous satellite constellations for internet connectivity. Emerging technologies can be leveraged to bridge this gap and ensure continued success in this frontier. This paper will provide a model to assist the Coast Guard in making future source-selection analyses of commercial communications satellite systems capable of providing service in the polar regions. This model was developed using techniques designed for multi-objective decision-making (MODM) and can be tailored to future organizational needs.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAF	Adaptive Acquisition Framework
ACAT1D	acquisition category for major defense acquisition with defense acquisition executive as milestone decision authority
AI	artificial intelligence
AIS	Automatic Identification System
AoA	Analysis of Alternatives
A2/AD	anti-access, area-denial
A-SAT	anti-satellite
C4I	command, control, communications, computers, and intelligence
C5ISR	command, control, communications, computers, cyber, intelligence, surveillance, and reconnaissance
CBA	cost–benefit analysis
CDD	Capability Development Document
CDO	contested, degraded, and operationally limited
CEA	Cost-Effectiveness Analysis
CGOne	Coast Guard network
COMSATCOM	commercial satellite communications
DISA	Defense Information Systems Agency
DOD	Department of Defense
EEOA	Economic Evaluation of Alternatives
EPS	Enhanced Polar System
FCC	Federal Communications Commission
FRC	Fast Response Cutter
GEO	geosynchronous orbit/geostationary orbit
GS	government service
HEO	highly elliptical orbit
ICD	initial capabilities document
IPS	Interim Polar System
ISR	intelligence, surveillance, and reconnaissance
ISS	International Space Station

KBps	kilobytes per second
Kbps	kilobits per second
KPP	key performance parameter
KSA	key system attribute
LEO	low Earth orbit
MBps	megabytes per second
Mbps	megabits per second
MCDM	multi-criteria decision-making
MDA	Maritime Domain Awareness
MEO	medium Earth orbit
MILSATCOM	military satellite communications
MODM	multi-objective decision-making
MOE	measure of effectiveness
MRL	manufacturing readiness level
ms	milliseconds
MTBF	mean time between failure
MTS	Maritime Transportation System
MUOS	Mobile User Objective System
NIPR	non-secure internet protocol router
NSC	National Security Cutter
ORD	Operational Requirements Document
PNT	positioning, navigation, and timing
PSC	Polar Security Cutter
RDC	Research and Development Center
SATCOM	satellite communication
SIGINT	Signals Intelligence
SIPR	secure internet protocol router
SLA	service level agreement
TISCOM	Telecommunications Information Systems Command
TRL	technology readiness level
UAS	unmanned aerial systems
UHF	Ultra High Frequency

ULA	United Launch Alliance
USCG	United States Coast Guard
VDI	Virtual Desktop Infrastructure
VoIP	Voice Over IP
WGS	Wideband Global SATCOM

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EXECUTIVE SUMMARY

With global warming contributing to a reduction of ice in the Arctic, vast resources previously inaccessible due to the ice coverage are now ripe for harvesting (*Climate Change*, 2019). However, the United States Coast Guard's (USCG) heavy icebreaker fleet is beleaguered at best. The U.S. government has identified a shortfall in capability and has committed to fund the new Polar Security Cutter to help protect U.S. territories and U.S. allies from potential military threats in the Arctic (USCG, n.d.). While technology has come a long way in the 50 years since the last heavy icebreaker was built in the United States, one considerable gap remains: Arctic communications networks.

The current USCG afloat assets use satellite communications (SATCOM) for off-shore internet connectivity. The modern fleet requires this capability to conduct daily missions, maintain communications with the operational commander, access and disseminate intelligence, and operate various service-specific enterprise applications. While not the most modern solution, the current SATCOM systems are functional and facilitate the minimum level of mission essential communications in most areas of operation. The SATCOM services procured by the USCG are geosynchronous satellites, or GEO, which has proven impossible to use by icebreaking assets in the Arctic as well as Antarctic regions. One of the primary issues that exists with this mode of communications is that the satellites lose connectivity with the shipboard antennae in extreme latitudes. This is due to the curvature of the earth and the fact that all GEO satellites are on an equatorial orbit (Bekkadal, 2014). For this reason, GEO SATCOM is not a viable form of communications for assets operating in the polar regions. This paper looks to explore the important features of satellite communications, potential solutions to the current capability gaps, and finally to develop a model for choosing a new system to enable our Arctic assets once technological solutions mature and become available.

SATCOM performance is primarily linked to three different characteristics: latency, bandwidth, and signal quality (D. Cote, personal communication, September 1, 2020). Latency, or the time it takes for the signal to travel from the point of origin to the destination and back, is largely dictated by the distance of the satellite from the earth's

surface (Newton, 2013). The Coast Guard has highlighted that latency, above all other performance factors, has the greatest impact on an asset's ability to connect to the USCG network effectively (D. Cote, personal communication, September 1, 2020). Bandwidth is the amount of data that can be transmitted at any one time (Newton, 2013). The amount of bandwidth available to a given cutter depends on the type of cutter and can often be increased or decreased by a SATCOM service provider. Finally, the signal quality is directly linked to the frequency of the transmission. Signal quality would describe a signal's ability to penetrate through the atmosphere or any weather conditions. These performance factors were the starting point for developing a model to assist in choosing an optimal SATCOM solution for the USCG's polar assets.

A number of different decision models were explored, and we decided that the Multiple Objective Decision-Making model (MODM) best fit the information available to us. This model breaks down a particular decision into a hierarchy, assigns weights to each component, and develops value functions to effectively striate the various options available (Wall & Mackenzie, 2015). These numbers are then aggregated into one overarching measure of effectiveness, or MOE, for each potential solution. While the performance characteristics of a new SATCOM technology are the most important, there are other factors that must be considered. Supportability, signal characteristics, and technical risks were all considered in the formation of our model.

The model developed from this research can be used as a tool for a source selection team to decide the overall best SATCOM proposal for the new Arctic assets. As the USCG further details their supportability requirements, the requirements can become more granular and be represented in a similar fashion to the performance aspects of the system. Finally, this research has revealed that some of these new and emerging SATCOM solutions could be used not only in the Arctic and Antarctic, but throughout the rest of the fleet as well. These new communications technologies, and their low-latency connections could have dramatic effects on the usability of many pieces of legacy software. Additionally, with a more useable network, new and innovative ways of conducting business in the Arctic and throughout the fleet could be realized.

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I. INTRODUCTION

Climate change has opened pathways within the Arctic previously inaccessible without the use of heavy icebreakers (*Climate Change*, 2019). The accessibility of this new frontier has paved the way for vast opportunities such as abundant fisheries, a plethora of natural resources, and shortened pathways to transport goods across the globe (United States Coast Guard [USCG], 2019). Along with these opportunities come potential challenges. Both Russia and China have increased operations in the area over the last few years. Russia alone has built 14 icebreakers and six Arctic bases within the last six years, reasserting itself as one of the most well-equipped Arctic nations (USCG, 2019). China, a non-Arctic nation interested in taking advantage of these newly accessible trade routes and resources, has executed six Arctic expeditions since 2013. The Chinese push into the region has solidified them as a "near-Arctic state" (USCG, 2019). In response to these changes, the United States Coast Guard (USCG) convinced lawmakers to make a much overdue investment in their aging icebreaker fleet, ensuring the service can continue to enforce laws and treaties in this unique operating environment. The Polar Security Cutter (PSC) program is the title of the new cutter acquisition which awarded a contract for the design and construction of the first heavy icebreaker since the late 1970s. This new program has paved the way for a potential of five additional assets prior to the culmination of the program (USCG, n.d.). While strides are being made with regards to major asset acquisition, a potential technological hurdle still exists that could prevent optimal operations in the contested Arctic—there are very few satellite communications companies operating in the polar regions.

A. CLOSING THE ARCTIC'S COMMUNICATION GAP

Historically, the USCG's large cutter fleet has maintained communications through the use of Inmarsat satellite technology. One of the Inmarsat's satellite constellations for providing connectivity is comprised of an array of four geosynchronous (GEO) satellites arranged to provide communications across the majority of the earth's surface (Inmarsat, n.d.). While GEO satellites have been a primary means of marine communication for the

last 40 years, they do not come without their drawbacks. To begin with, GEO satellites are located along the earth's equator, slightly more than 22,000 miles from the planet's surface. For a signal to travel from the earth to the satellite and back again (round trip time), it must travel twice that distance. This could take between 500 and 1000 milliseconds (Ou, 2008). This travel time, or *latency*, exceeds the requirements necessary for a communications signal to be considered broadband and makes operations slower than ideal when leveraging this technology. While this does not completely hinder operations, it does make them more complicated as high-latency connections tend to degrade web-based applications. Broadband internet is discussed further in Chapter II, Section G.

Furthermore, GEO satellites are relatively low in resiliency. As is seen in Figure 1, a large portion of the globe could exist without adequate communications should one of the satellites be damaged or destroyed. Notably, China destroyed one of their retired weather satellites in 2007, demonstrating to the world that they had this capability (David, 2007). Additionally, since Inmarsat is a commercial company, there may be questions as to whether the communication signals can guard against cyber-attacks, also within the arsenal of the U.S. adversaries such as China or Russia. The low number of satellites in GEO constellations coupled with their unknown cyber protection capabilities poses a risk for satellite communications. While both these issues are fairly concerning, they apply equally to all areas of the globe. One of the biggest concerns in the Arctic and Antarctic regions has to do with GEO satellites and their inability to see the northern and southern extremes of the earth's surface.

As all GEO satellites are located on an equatorial orbit, the elevation angle from the terminal to the satellite decreases the farther one gets from the equator. At just over 81 degrees latitude, the elevation angle reaches zero; thus any further north in the northern hemisphere or south in the southern hemisphere and the GEO satellites will be completely blocked by the curvature of the earth (Bekkadal, 2014). This is visually represented in Figure 1.

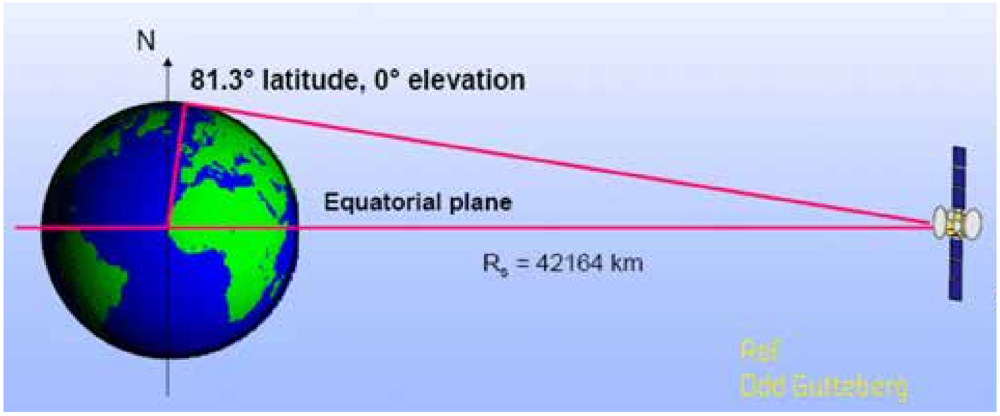

Figure 1. Representation of Equatorial Orbit of GEO Satellites. Source: Bekkadal (2014).

Realistically, the signal starts to degrade at roughly 65 degrees latitude, further complicating Arctic operations. The elevation angle affects the line of sight, and as the angle decreases, the amount of atmosphere that the signal needs to pass through increases (Bekkadal, 2014). This is the primary reason that new technology needs to be explored as the landscape becomes a hotbed for Arctic and near-Arctic nations.

One of the key tenets in the United States Coast Guard's (2019) Arctic strategic outlook is to "close the communications gap in the Arctic" (p. 6). While the document itself focuses on leveraging strategic partnerships in the area, there are potential technologies coming online that could enable the USCG to meet this goal sooner than expected. From a more localized approach, the ability to meet or exceed broadband communications requirements within the Arctic region could be added to the requirements documents for the current Polar Security Cutter acquisition. This would force the current shipbuilder to partner with SATCOM technology stakeholders to leverage cutting edge solutions to the challenges of polar communications. On a more macro scale, a program encompassing all major assets within the service could be started within the command, control, communications, computers, cyber, intelligence, surveillance, and reconnaissance (C5ISR) acquisitions directorate, deriving a more complete solution to worldwide service-based communications challenges. Either approach champions a new vantage point, starts the process to solve a major strategic goal, and provides a look at the newest technological innovations capable of addressing some of the GEO satellite communications shortfalls.

Two different approaches are being explored within the satellite communications space to address some of the shortfalls associated with geosynchronous orbit satellite communications. One technology that has been around for a number of years is medium Earth orbit, or MEO, satellite technology. These satellites are put into orbit roughly 5,000 miles off the earth's surface (Gallaugher, 2019). This is a quarter of the distance of the GEO orbit. Due to the close proximity to Earth, 20 MEO satellites are needed to ensure optimal communications across the earth's surface as compared to the three or four GEO satellites. While the number of satellites is greater, their size can be reduced, and their power requirements are much less due to the signal itself needing to travel a far shorter distance.

The final satellite communication approach that has been explored more recently is the low Earth orbit (LEO) satellites. These communication satellites are much smaller than their GEO and MEO counterparts, and orbit the earth at roughly 750 miles off of the surface (Patterson, 2015). Due to the close proximity to the earth's surface, hundreds of these satellites are needed to fully cover communications across the earth's surface. Some companies are even proposing launching thousands of satellites to ensure optimal coverage (Patterson, 2015). As the LEO satellites are stationed on the closest Earth orbit, their signal power requirements are the least demanding, making these the smallest of all communications satellites. Additionally, because they are so close, they have the capability to meet broadband communications latency requirements, something not previously achieved by the GEO or MEO technology. The networked nature of the LEO satellites described would ensure 100% coverage of the earth's surface including both the Arctic and Antarctic regions, solving the elevation angle issues as previously outlined with GEO satellites.

Outside of the satellite communications space, other companies have investigated the potential use of unmanned aerial systems (UAS) to transmit signals in hard to reach spaces. Google explored the possibility of sending out signals from unmanned air balloons while Facebook delved into unmanned, solar powered drones to transmit broadband internet to rural areas of the globe (Gallaugher, 2019). While novel in concept, both technologies were aimed at underdeveloped or rural areas of countries with little to no

terrestrial internet (fiberoptic, cable, cellular). Most of these concepts have stagnated and their use in the polar regions could be problematic due to environmental and geographic concerns. At this time, it is unknown if there are any proposals for adopting the innovative satellite or UAS technology for military marine applications. Also, there is no public record that either of these concepts are viable within the harsh climates of the Arctic and Antarctic regions of the globe. The application of this technology is briefly explored in the future research section of this paper.

B. TECHNOLOGY HORIZON

As previously outlined, the emergence of MEO and LEO satellite communications has introduced technology that could not only address communications deficiencies in the Arctic and Antarctic regions but could also combat the latency and resiliency issues associated with legacy GEO satellite communications. For the purposes of this paper, the focus is on LEO satellites as most of the companies involved in furthering global communications are concentrating their efforts in this domain. The issue that should be addressed first is the barriers which have been removed to facilitate the use of LEO satellites for communications. The predominant reason this method of communications is now feasible is linked to the commercialization of space. Fifty years ago, space travel was government funded and used to further national interests. While this was effective in ensuring governmental control over space flight, there were few incentives to reducing the cost of manned and unmanned space travel. Government regulations in the United States largely prevented the use of technology outside of NASA's purview (Congressional Budget Office [CBO], 1986).

In 1980, Arianespace was founded as a joint public/private sector initiative in Europe providing government funds for building the required launch infrastructure and hardware, and then transitioning the company into private ownership. In the early 2000s, companies such as Space X and Blue Origin were founded, furthering the commercial space landscape (Carr, 2016). Space X has developed rockets capable of being recovered after launch, further reducing the cost per flight. The continual reduction in cost per launch has paved the way for launching small satellites into low Earth orbit. As previously

mentioned, unlike their GEO and MEO counterparts, to ensure communications across the globe, hundreds of LEO satellites must be launched into orbit. Reduction in the size and weight of the satellites being used, coupled with the reduced cost of launching rockets into space has paved the way for installing a constellation of LEO satellites capable of facilitating broadband communications.

The strategic potential to the U.S. Coast Guard for leveraging this emerging technology is vast. While the LEO satellite architecture has been tested, it is not expected to be fully operational until 2021 or 2022 (Clark, 2020). With that in mind, this timeline will still predate the arrival of the first PSC, which is slated for early 2024 (USCG, n.d.). The potential exists to add the capability within the current requirements for this new Coast Guard asset. Should the PSC be fielded with this new technology, it will place the Coast Guard above its current competitors in the Arctic region with regard to communications capability. While the service has no plans on matching the number of icebreakers fielded by Russia, having capable assets that are connected to broadband internet ensures that the crew of the vessel has access to all USCG IT services. This allows for direct communications with operational commanders, real-time logistics reporting and updates, along with vital communications to USCG aviation assets. Additionally, should the polar space become contested, having robust communications with Department of Defense (DOD) counterparts will be instrumental to the success of the United States in the region.

C. RESEARCH OBJECTIVES

The ensuing research hopes to address the following questions:

1) What commercial satellite communication (SATCOM) technologies are currently available?

2) What SATCOM characteristics are optimal for communication within the arctic region?

3) What communication characteristics does the USCG value?

4) How can the first three objectives be used to develop a decision model for choosing the optimal Arctic communication technology?

As previously outlined, the Arctic has become a hotbed for activity in recent years. The USCG has been charged with keeping the waterways navigable in that region and recently awarded a contract to build the nation's first heavy icebreaker in over 40 years. While the mechanical aspect of shipboard technology has changed very little with regard to icebreaking, the service's reliance on IT systems to conduct its day to day missions has increased exponentially since the last icebreakers were fielded. The hope is that through this research a decision tool will be developed to aid the service in either refining SATCOM requirements for the current PSC acquisition or for developing requirements and awarding a future C5ISR contract to better support the USCG's communications needs in the polar regions.

Although some insights can be gained in studying satellites used for positioning, navigation, and timing (PNT), this paper focuses on communications satellites and capability gaps for Arctic communications. In addition to a deep dive into SATCOM, this research also briefly looks at various decision models used within the private sector and the DOD for making complex decisions. One particular variant is adopted and developed specifically for deciding which satellite service provider to use for Arctic communications. While certain cutting-edge technologies are in their infancy, it is this paper's objective to provide as much detail to the model as possible while allowing for future refinement of the model as next generation SATCOM becomes more mature and operational requirements change.

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II. BACKGROUND AND LITERATURE REVIEW

With the regression of polar ice, shipping routes are becoming available in the Arctic and industries are considering the exploitation of resources in the region. In the coming years, the USCG expects to see increased traffic for “resource extraction, fisheries, adventure tourism, and trans-Arctic shipping” (USCG, 2018b). The Arctic also contains an estimated 13% of the world’s undiscovered oil, and 30% of undiscovered natural gas (Gautier et al., 2009). Given these resources, the Arctic Circle has the potential to become an area of contention between the United States and other Arctic nations (such as Russia) seeking to extract these resources.

Out of the eight Arctic nations, the United States is underrepresented when it comes to icebreaking capabilities (Drewniak et al., 2018). The United States lags behind other Arctic nations in both the number and capabilities of Arctic icebreakers (Gilmour, 2018). The Arctic is a vast area, and the Coast Guard’s ability to project a U.S. presence is critical in maintaining U.S. interests as an Arctic nation (Allen, 2017). This chapter will explore the USCG Arctic missions, polar communication technology gaps, and explore current technology trends that may be leveraged to address some communications shortfalls.

A. THE COAST GUARD’S ARCTIC MISSION AND GAP ANALYSIS

The Coast Guard’s Arctic mission set mirrors many of its statutory missions: law enforcement, fisheries preservation, environmental protection, facilitating safe commercial activity, and providing search and rescue capability along the United States’ shores and waterways (USCG, 2019). The USCG’s 2019 Arctic Strategic Outlook stated, “The Coast Guard will protect the Nation’s vital interests by upholding the rules-based order in the maritime domain while cooperating to reduce conflict and risk. We will help safeguard the Nation’s Arctic communities, environment, and economy” (USCG, 2019, p. 6). This document emphasized the need to promote and enforce the rule of law in the area. As a result of climate change and an increase in maritime activity, there will likely be an increase in the number of mariners found in distress throughout the Arctic region. These changes in

this operating area makes it imperative that the Coast Guard pursues innovative approaches to enabling mission success (USCG, 2019).

Recently, the Coast Guard awarded VT Halter with a $745 million contract to build one heavy icebreaker with delivery of the vessel no later than 2024. Within this contract, two options exist for additional assets (up to six) that could propel the total contract value up to $1.9 billion (Buchanan, 2019). Senator Cindy Hyde-Smith of Mississippi correctly stated, “These advanced ships will help address national security, law enforcement, and humanitarian missions in the polar regions” (Buchanan, 2019).

Abbie Tingstad, a senior physical scientist, associate director of the Engineering and Applied Sciences Department at RAND Corporation, and a security research expert, has called out specific gaps in Arctic capabilities in testimony before Congress. One such gap was identified as the lack of internet connectivity. It was of particular note that possible mitigation strategies include utilization of the increasing number of commercial satellite systems in orbits over the poles (*Climate Change*, 2019). Additionally, William Dwyer, in his 2009 research paper on changes in the Arctic, argued that there should be a “quad track approach” to Arctic policy, focusing on diplomacy, homeland security, defense, and commerce (Dwyer, 2009, p. 75). To support these activities, the USCG highlighted reliable high-latitude communications as a key enabler for Maritime Domain Awareness (MDA; USCG, 2019).

The Coast Guard is uniquely suited to this “quad track approach,” and has a history of serving in all four of these realms while working with partner agencies and allied nations. It is apparent that over the last 20 years, the Coast Guard has fallen behind regarding communications technology. This has increased the difficulty of maintaining effectiveness and competitive advantage across the four realms of the “quad track approach.” The USCG has identified the incorporation of new technologies as key drivers to improve the Coast Guard’s efficiency in the Arctic and Cyber domains (USCG, 2018a). As the operators of the nation’s only two operational polar icebreakers, the U.S. Coast Guard is uniquely positioned to continue executing its missions in the Arctic and Antarctic. Internet service has not changed significantly for Coast Guard cutters since the early 2000s. The new PSCs will be a step in the right direction, as they will provide a much needed replacement to the

legacy polar icebreakers currently in operation, but unless something changes, they will continue to operate without connectivity once they travel to their operating areas in the extreme latitudes. To maintain effective MDA throughout the resource-rich Arctic, information sharing is critical. High latitude communication networks remain “a whole-of-government challenge” that will require extensive partnerships (USCG, 2019).

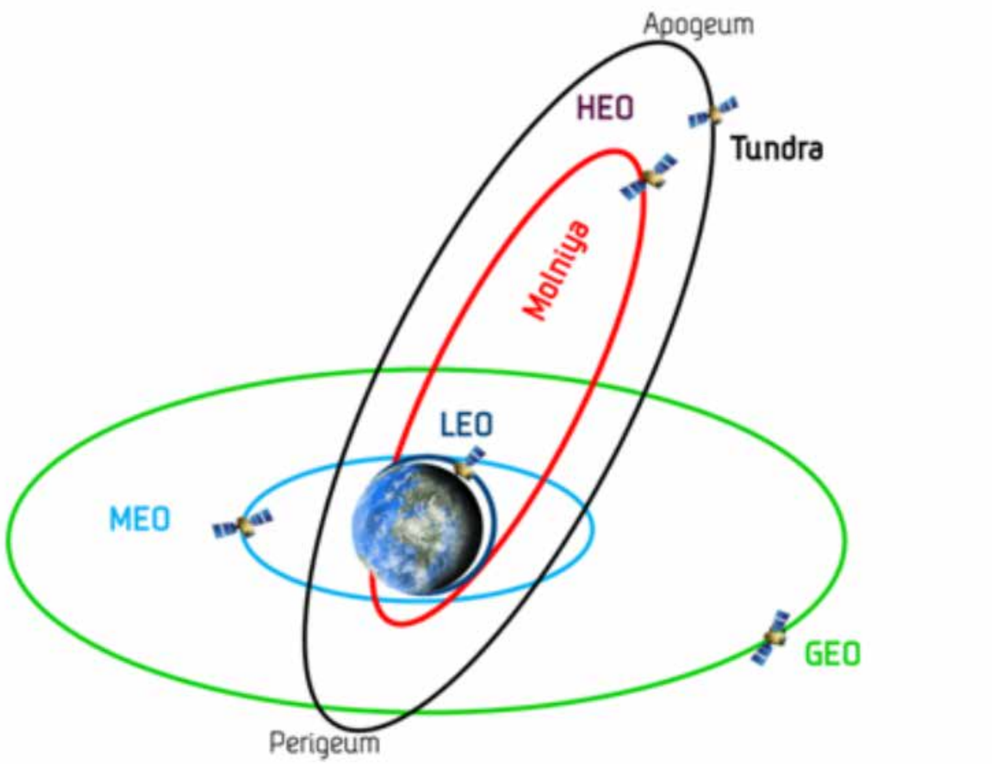
B. CURRENT USCG SATCOM TECHNOLOGY AND INHERENT POLAR ISSUES

The Coast Guard’s current large cutter connectivity solution relies on Inmarsat SATCOM systems, even for the polar ice breakers (Inmarsat, n.d.). These constellations require very few satellites to provide global coverage due to their geosynchronous (GEO) orbits. While GEO satellites have been a primary means of marine communication for years, they do not come without their drawbacks. All GEO satellites are located along the earth’s equator, slightly more than 22,000 miles from the planet’s surface. For a signal to travel from the earth to the satellite and back, it must travel approximately 44,000 miles, taking between 500 and 1000 milliseconds (Ou, 2008). This travel time, or latency, makes network use slower than ideal when leveraging this technology (Newton, 2013). While this does not completely prevent cutters from connecting to the Coast Guard network (CGOne), high-latency connections tend to degrade the usability of web-based applications.

Polar icebreakers are also equipped with the same shipboard terminals to connect to Inmarsat’s GEO constellations, but service becomes unavailable to these cutters in the extreme latitudes where they are designed to operate. This occurs because of the equatorial orbit of the GEO satellite constellations. The elevation angle, or the angle at which one needs to point a satellite dish to make a connection to a given satellite, decreases the farther one gets from the equator. Due to the curvature of the earth (see Figure 1), GEO constellations are simply infeasible SATCOM solutions for the polar regions without some sort of complementary technology.

C. EXISTING AND EMERGING SATCOM ALTERNATIVES

A key goal within the U.S. Coast Guard's Arctic Strategic Outlook is to "close the communications gap in the Arctic" (2019). Two different approaches are being explored within the satellite communications industry outside of the preexisting geosynchronous satellites which may provide high speed communications in the polar regions. One technology that has been around for several years is known as a medium Earth orbit, or MEO, satellite communications (Gallaugher, 2019). Unlike their GEO counterparts, MEO satellites are not necessarily located along the equator. Figure 2 illustrates the orbital characteristics of GEO, MEO, and LEO satellites. MEO satellites are placed into orbit roughly 5,000 miles from the earth's surface (Gallaugher, 2019). At this altitude, approximately 20 satellites are needed to ensure communications to the majority of recipients as opposed to the four GEO satellites needed to provide an internet connection around the globe. While the number of satellites is greater for MEO, their size and signal power requirements are reduced due to the signal itself needing to travel a far shorter distance. Since MEO satellites are approximately a quarter of the distance of the satellites in GEO orbit, this significantly reduces the amount of latency involved in the round-trip times (Ou, 2008).



Orbit		Altitude [km]	
		Apogeum	Perigeum
LEO: Low Earth Orbit		200 – 2 000; normally: 600-1 000	
MEO: Medium Earth Orbit		2 000-GEO; normally: 10 000-20 000	
GEO: Geostationary Orbit		35.786	
HEO: High Elliptical Orbit	Molniya (12 hr)	~500	~40 000
	Tundra (24 hr)	~24 000	~48 000

Figure 2. Visualization of Different Orbits Used for Satellite Systems. Source: Bekkadal (2014).

The other satellite communication approach that many companies recently have invested in is the LEO satellites (Patterson, 2015; Telesat, n.d.). These communication satellites are much smaller than their GEO and MEO counterparts and orbit the earth at roughly 750 miles from the surface. Due to this close proximity, hundreds of these satellites are needed to fully cover communications across the earth's surface. Several companies are even proposing launching thousands of satellites to ensure optimum coverage (Patterson, 2015). LEO satellites are of particular interest when discussing modern communications networks because they provide the lowest theoretical latency of any satellite-based communications system.

Both the upcoming MEO and LEO solutions are no longer based on an equatorial orbit like the GEO communication satellites. This does away with the line of sight limitations affecting polar communications that are normally posed by the GEO satellites because of their orbital characteristics. Telesat intends to begin offering service as early as 2022 and boasts on their website of “inter-satellite links” that would enable communications to be relayed across a mesh network of satellites to efficiently connect a mobile user regardless of where they are on the planet (Telesat, n.d.). Other companies undoubtedly have similar solutions in mind for optimizing their network traffic and keeping latency low. The architecture of some of the proposed LEO constellations would ensure 100% coverage of the earth’s surface including both the Arctic and Antarctic regions, solving the elevation angle issues as previously outlined with the GEO satellites (Bekkadal, 2014; Telesat, n.d.).

The low number of GEO satellites, coupled with their unknown cyber protection capabilities, poses a high risk for current satellite communications. While both of these issues are fairly concerning, they apply equally to all areas of the globe. As the newly-minted military satellite communications service provider, the U.S. Space Force has identified the need for resiliency in their networks in order to maintain the military’s “asymmetric advantage of global space-based communications” (U.S. Space Force, 2020, p. 1). In order to be truly global, this resiliency should include polar communications. Out of necessity, LEO and MEO satellite systems have more satellites within their constellations than their GEO counterparts. In this regard, some may consider that LEO and MEO constellations are inherently more resilient. An increased number of targets means that a kinetic attack (or potentially cyber-attack) would need to neutralize more objects to interrupt communications.

The argument to leverage LEO and MEO orbits is not new. In her 2019 testimony before Congress, Abbie Tingstad stated, “Communications networks also will enhance reach across, into and out of the Arctic,” and stated the first mitigation strategy for the United States’ lack of Arctic capabilities as leveraging “the growing number of commercial communications satellites in polar orbits” (*Climate Change*, 2019). As far back as 2002, one Coast Guard study noted the limitations of GEO and recommended using LEO

satellites (USCG, 2002). The commercial systems in Tingstad's testimony would almost certainly be in the LEO or MEO orbits, as there is no evidence that a highly elliptical orbit (HEO) above the north or south poles would be commercially viable for private industry. It is known that the military utilizes HEO orbits (King & Riccio, 2010); the potential for these orbits is discussed further in the future research section.

D. FLEETWIDE BANDWIDTH AND LATENCY

Coast Guardsmen have called for increasing cutter bandwidth over the years (Allen, 2019). Bandwidth, or the amount of data that can be transmitted at a given time (Newton, 2013), is certainly an issue onboard the Coast Guard's ships. Implementing a higher bandwidth solution will undoubtedly help the fleet but is not the only network characteristic that matters. Latency is also a critical factor, and in their 2002 study of U.S. Coast Guard cutter connectivity, the Coast Guard determined latency was the major limiting factor. Web-based applications and websites have likely only become more demanding since then, and little can be done to improve the performance of GEO satellite systems based on the altitude at which they orbit (USCG, 2002). Through their low latency, and potentially higher bandwidth availability, LEO or MEO satellites could not only provide a solution to the Arctic communications gap, but also provide a drastic improvement to the communications capability of the rest of the USCG's cutter fleet.

E. COMMERCIALIZATION OF SPACE

While MEO satellite technology has been viable for a few years, leveraging this technology has been largely cost prohibitive (Valinia et al., 2019). Additionally, LEO satellite communications are still in their infancy, with most mature companies having only about 30% of the satellites needed for global coverage in orbit (Clark, 2020; Thompson, 2020). Previously, one of the biggest hurdles in allowing MEO and LEO satellite technology from gaining technological maturity has been the government's monopoly regarding space travel. Government regulations in the United States largely prevented the use of technology outside of NASA's purview. The Space Shuttle Challenger disaster is cited as having raised concerns surrounding national space policy, which led to the initial commercialization of space travel by large government contractors (CBO, 1986).

In 2014, SpaceX filed a lawsuit against the federal government for not allowing SpaceX to compete for a rocket contract that was awarded to United Launch Alliance (ULA), a joint venture of Lockheed Martin and Boeing (NBCNews, 2014). Since this noteworthy lawsuit, not only has SpaceX been certified to compete for space-related contracts, but SpaceX and other companies have made huge strides in competing in the multi-billion-dollar space industry. The satellite industry is mainly concerned with two areas for significant growth potential: Earth observation and broadband internet services (González, 2017).

A new era in space exploration and travel appears to have arrived, with the goal of making space a profitable commercial venture. On May 30, 2020, SpaceX made history by fulfilling a contract with NASA to deliver astronauts to the International Space Station (ISS). These were the first astronauts to launch from U.S. soil since the Space Shuttle program ended in 2011 (Wall, 2020). On June 13, shortly after their mission to the ISS, SpaceX launched a Falcon rocket with a payload of 58 StarLink satellites, their LEO communications solution. This was the ninth of these launches to successfully carry communications satellites into orbit since May 2019. In just under 13 months, SpaceX has successfully launched 540 satellites into orbit (Thompson, 2020).

Historically, space has been prohibitively expensive for new entrants. The emergence of small satellites (often referred to as CubeSats, or SmallSats) used for experimental and educational purposes have driven innovation in the miniaturization of satellite technology. These developments have greatly lowered the cost to produce satellites, and through the reduction of weight, reduced the cost of launching satellites (Valinia et al., 2019). As new governmental and private institutions seek to capitalize on the unique environment of space, rocket companies should be able to improve their bottom lines by delivering CubeSats and traditional satellite systems into orbit. This would ultimately help improve access to the commercial use of space (González, 2017). To drive competition further and reduce costs, the founder and CEO of SpaceX, Elon Musk, desires to make as much of SpaceX’s rocket systems reusable as possible. By June 2020, a remarkable 54 first-stage boosters have been recovered successfully (Thompson, 2020).

F. BROADBAND INTERNET ACCESS

For an internet connection to qualify as broadband, the bandwidth or transmission speed must be at or greater than 10 megabits per second (Mbps) downstream and one Mbps upstream (Federal Communications Commission [FCC], n.d.). As Americans, we generally take internet access for granted. According to a 2016 study by the Federal Communications Commission, more than 95% of Americans have access to broadband internet (Whitacre et al., 2018). However, an article by Thom Patterson (2015) stated that "57% of the world's population was still offline." LEO satellite technology could be the solution to this problem and help bring internet to all the world's citizens. Not only do the characteristics of LEO ensure lower latency communications, but they could also ensure that LEO satellite providers are partially subsidized by the government for providing low-latency, high-bandwidth internet connections to rural areas. This is a primary goal of the Federal Communications Commission's Connect America Fund, which seeks to subsidize internet service providers (including broadband SATCOM) for infrastructure costs (FCC, n.d.).

Investment by the government (through military spending or through the FCC's subsidization), and by private industry seeking to provide broadband internet to anyone, anywhere on Earth, will contribute to the likelihood of success for LEO and MEO satellite communications service providers. Plans for LEO satellite constellations are being developed and rolled out by companies such as OneWeb, SpaceX, and Telesat. These constellations will be located between 600 and 800 miles from the earth's surface, a 96% reduction in distance from their GEO counterparts (Patterson, 2015). This represents a significant reduction in the time it takes for the signal to travel from a terrestrial terminal up to the satellite and back down to Earth. This interest in broadband is likely to make SATCOM commercially viable for a large user group in the near future. As a byproduct, those in the polar regions could benefit from the widespread adoption of LEO and MEO systems.

G. SATCOM SERVICE PROCUREMENT, MILSATCOM, AND OTHER CONSIDERATIONS

The Coast Guard is not alone in the limitations of its connectivity. One of the DOD's primary communications satellite systems for mobile users, Wideband Global SATCOM (WGS), is designed to provide connectivity only from 70 degrees north latitude to 65 degrees south (Strout, 2020). Unlike the Coast Guard, the DOD does have a dedicated system for polar satellite communications known as the Enhanced Polar System, or EPS. Very little public information is available describing the capability of EPS; however, what is known is that it is currently operated by Space Force and "provides secure, anti-jamming signals and is built for high priority military communications" (Keller, 2020). Potentially partnering with the DOD and leveraging their capabilities could be an option to bridging the current communications gap for the USCG. This is explored in the future research section of this paper.

From a commercial satellite perspective, hurdles do exist to implementing these new systems across both the DOD and the rest of government. For example, there is cybersecurity policy concerning satellites, which sets forth security and encryption guidelines for these new LEO systems, specifically "end-to-end" encryption of all data (Committee on National Security Systems, 2018). Whether these systems will meet these standards remains to be seen. Other drawbacks include the increased number of objects in orbit. With thousands of pieces of debris currently in orbit, "space junk" is a real concern as satellites can collide with one another or be damaged by even the smallest piece of debris (Kharpal, 2020). The StarLink system alone will exceed 4,000 new satellites (Gallaugher, 2019). Additionally, with the current economic state, OneWeb has had to file for bankruptcy, potentially impacting the rollout of this new system (OneWeb, 2020). StarLink, on the other hand, is facing increasing pressure from the FCC about potential false claims that their signal will meet the latency requirements to be considered a broadband system (Brown, 2020). Despite these setbacks, both systems could be up and running in some capacity within the next year or two. Once fully rolled out, this could ensure internet for the masses and potentially facilitate vital military operations in areas previously underserved by internet service providers.

Proposed solutions will require additional consideration to obtaining Defense Information Systems Agency (DISA) certification. In addition to requiring NSA-level encryption (research was unable to determine whether any of these systems would achieve this), DISA also requires "end-to-end" systems to be leveraged in providing SATCOM connectivity (Defense Information Systems Agency, 2017). Whether all these new services can meet these high standards is unproven, but there is no specific documentation that would prevent LEO or MEO solutions from achieving the same level of security that the GEO solutions are currently employing.

H. THREAT ANALYSIS

In modern times, all environments need to account for cyber security. The 2018 National Cyber Strategy emphasized the importance of a growing cyber threat. This included a reference to a threat of our "space assets and supporting infrastructure" (White House, 2018, p. 10). This cyber threat to our space-based systems has obvious military implications, as an enemy would greatly benefit from eliminating the ability of warfighters to communicate with command and control entities. However, these space assets also play a critical role to the national Maritime Transportation System (MTS) and other civilian systems throughout the world and the Arctic. According to the National Cyber Strategy, government and civilian satellite systems are "critical to functions such as positioning, navigation, and timing (PNT); intelligence, surveillance, and reconnaissance (ISR); satellite communications; and weather monitoring." (White House, 2018, p. 10) Additionally, this document states that "the Administration will enhance efforts to protect our space assets and support infrastructure from evolving cyber threats, and we will work with industry and international partners to strengthen the cyber resilience of existing and future space systems" (White House, 2018, p. 10).

China, a non-Arctic nation, has executed six Arctic expeditions since 2013 looking to take advantage of newly accessible shipping routes. The Chinese push into the region has demonstrated their interest in not just being able to operate their navy in harsher climates, but also to leverage Arctic routes for the reduction of shipping costs. This has led them to self-proclaim as a "near-Arctic State" (USCG, 2019, p. 10). As such, the country

of China, and their military capabilities, need to be taken into consideration when assessing the Arctic and military communications capabilities in the region. Although China is known for their prolific activity in cyberspace (where the potential to render satellite systems inoperable could exist), they have also demonstrated their ability to destroy satellites with more conventional means. Of particular note, China destroyed one of their inoperable weather satellites in 2007 with an anti-satellite (A-SAT) missile (David, 2007). As previously discussed, the fact that LEO and MEO satellites have more satellites in their constellations gives them a potential edge against their GEO counterparts when considering resiliency. Additionally, for both cyber and more conventional A-SAT considerations, having access to numerous SATCOM systems may be in the best interest of the military in their quest for resiliency and flexibility.

The concepts of cybersecurity and resiliency are of critical concern. Although there are agencies specifically concerned with cybersecurity and actively trying to ensure the Coast Guard's networks are safe to conduct military and government business on, the research has uncovered an emergence of military interest in the resiliency of satellite systems (U.S. Space Force, 2020). With China's ability to attack a satellite, either via cyberspace or a kinetic strike, the U.S military is seeking resiliency through a greater distribution of satellite capabilities. General Hyten, the vice chairman of the Joint Chiefs of Staff in 2017, stated, "I will not support buying big satellites that make juicy targets" (Erwin, 2017).

Providing command and control capability is vital in a contested environment. If communications with forces on the front lines are lost, the warfighter will be profoundly disadvantaged. As the newly minted military satellite communications service provider, the U.S. Space Force has identified the need for resiliency in their networks:

> Despite the global, instantaneous reach of our SATCOM capabilities, which includes both military (MILSATCOM) and commercial (COMSATCOM) capabilities, the enterprise needs to improve its resiliency, robustness, flexibility, and manageability. In order for the United States to maintain its asymmetric advantage of global space-based communications, the SATCOM enterprise must evolve quickly. (U.S. Space Force, 2020, p. 1)

The Space Force's vision for SATCOM has implications for the next generation of satellite systems. The very nature of LEO satellite constellations, with their mesh solutions and numerous satellites overhead, would inherently provide a level of resiliency. Although legacy GEO systems, with just a handful of satellites per constellation, certainly do not fit this new vision for SATCOM, they may continue to be utilized for secure communications. However, they should not be solely relied upon as the only means of SATCOM. Instead, a multi-orbit, multi-frequency catalog of satellite services should be considered to provide the robustness the Space Force is looking for in providing the next generation of satellite communications (J. Shaw, personal communication, February 21, 2020).

I. SUMMARY

The USCG's increased role in the Arctic is evident in the government's commitment to recapitalizing the service's aging icebreaker fleet. One key technological hurdle that has yet to be addressed is the gap in communications within the Arctic region. The previous paragraphs have explored the current satellite communications and some of their shortcomings. Additionally, an overview of the commercialization of space and its role in the emergence of LEO and MEO satellite communications was also touched upon. Though not fully operational, these lower orbit commercial communications satellite systems stand to be a potential standout for not only addressing Arctic communications issues but also in providing broadband internet access to even the most remote regions of the world. This technology could ensure optimal internet connectivity for the future USCG Arctic assets. However, the service must be mindful of the resilience and reliability of these new systems to ensure that they are safeguarded against U.S. adversaries.

The various components of satellite communications is explored in the next chapter. The key system characteristics, various decision-making models, and the formulation of value functions will all help in deriving an overarching equation for evaluating future satellite communication technologies and ensuring the USCG picks the best, affordable technology. Also, it is important to note that the methodology will be focused on procurement of a commercial satellite communications service, as the USCG has yet to secure an agreement to leverage existing MILSATCOM capabilities operated by the DOD.

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III. METHODOLOGY

This chapter outlines a framework for assessing different satellite technologies. At the time of this research, the only operational satellite system identified that provided 100% global coverage (including polar regions) was the Iridium Certus constellation. Certus is a LEO satellite constellation comprised of "66 cross-linked satellites with multiple overlapping spot beams … enabling speeds of up to 352 Kbps transmit and 704 Kbps receive" (Iridium, 2020). Other satellite systems are on the horizon, with similar or greater capabilities likely. SpaceX's StarLink system, OneWeb, and Telesat LEO are other systems that are scheduled to be operational in the next few years (Del Portillo et al., 2018). Since pricing data is not available for any of these systems, this section aims to deliver a method with which decision-makers can consider different aspects of these systems independent of cost.

A. ASSUMPTIONS AND RATIONALE

The "two major pillars upon which most of modern decision analysis rests are theories of probabilistic reasoning and theories of value or preference" (Schum, 2016). Our analysis of commercial satellite communications (COMSATCOM) falls firmly in the latter category, requiring us to identify aspects of a system that are of value to its users. Before an Analysis of Alternatives (AoA) or Cost-Effectiveness Analysis (CEA) can be performed, key characteristics of a desired system need to be identified. This section outlines those attributes that should be considered when comparing the costs of systems to one another.

The analysis considers the following satellite characteristics:

· bandwidth

latency

· signal characteristics (namely, if the system may be affected by weather)

· supportability

Because we are concentrating on polar communications specifically, we did not directly include availability in our assessment. It is assumed that whatever system would be selected by the U.S. Coast Guard would have 100% global coverage and would exist in either a LEO or MEO orbit. Other potential technologies (high-atmosphere balloons, military satellite communications [MILSATCOM], and CubeSATs) that could be leveraged to solve the Arctic communications gaps are discussed in later chapters but were not considered in performing this analysis. These technologies are briefly addressed in the future research section of the paper.

Resiliency is another characteristic of satellite communications (SATCOM) that is understood to be of great importance. According to the Space Force, space-based communications must improve their resiliency along with their flexibility, robustness, and manageability. "In order for the United States to maintain its asymmetric advantage of global space-based communications, the SATCOM enterprise must evolve quickly" (U.S. Space Force, 2020, p. 1). This seems especially important when considering such systems on military vessels, particularly in the event of armed conflict. The resiliency of a given communications system should be well understood. Including this aspect of SATCOM technologies would have added unnecessary complexity to our analysis for several reasons, primarily that resiliency can be defined in numerous ways. Determining a satellite's resilience to cyberattacks was outside the scope of this research project. Likewise, determining the level to which a satellite is hardened against nuclear detonation, massive electromagnetic disturbances, or jamming efforts was also outside the scope of this research project. Finally, the likelihood of losing satellites to effects from the Van Allen radiation belt and atmospheric drag should also be considered when assessing these technologies. In considering resiliency in these LEO and MEO assets, an assessment of the "self-healing" aspects of the cross-link/mesh dynamic architecture of the inter-satellite links may also need to be conducted. The potential self-healing aspects of a given system were determined to potentially play into the assessment of reliability of that system. We discuss resiliency further in the chapter concerning future research and the concept of a software-defined satellite modem.

B. DEFINITION OF TERMS

In the previous section we outlined the characteristics important to SATCOM. In this section we will better define these characteristics to provide context for decision model development. Performance characteristics of current USCG SATCOM will also be discussed to provide context for minimum requirements in the Arctic operational area.

1. Bandwidth

Bandwidth is the amount of information that can be encoded and transmitted in a signal in a given amount of time (Newton, 2013). For IT professionals, this is represented as a data rate, usually in kilobits/megabits (Kb/Mb) or kilobytes/megabytes (KB/MB) per second. For clarity purposes, we represent the data we uncovered in bits per second (Kbps/ Mbps). In technical writings, bandwidth is often referred to as *throughput* (Newton, 2013). In signals processing terminology, bandwidth is an overly technical term that is not easily translatable into system requirements. Throughput is a better technical description of what this paper is concerned with, but we use the two terms interchangeably throughout.

A recent test conducted onboard a Coast Guard cutter by the Coast Guard's Research and Development Center (RDC) reported receiving 700 Kbps, which aligns with the advertised bandwidth capacities of the Certus system of up to 704 Kbps (Iridium, n.d.). Unfortunately, this is considerably below what the Coast Guard's cutter fleet demands. In discussions with the Coast Guard's Telecommunications Information Systems Command (TISCOM) and the RDC, the commercial satellite bandwidths available to the Fast Response Cutters (FRCs) and National Security Cutters (NSCs) were 2 Mbps and 6 Mbps respectively. Approximately 80% of this bandwidth is consumed at peak utilization. It would take three separate Certus links to provide the bandwidth required on an FRC, and about nine links for the NSC. At this point, this LEO technology does not appear particularly attractive to the Coast Guard, but there may be ancillary purposes for such a system onboard a Coast Guard cutter. At the time this research was conducted, the Coast Guard's RDC was in the midst of testing Certus onboard Coast Guard cutters for non-CGOne connectivity. These tests included Voice Over IP (VoIP) and one of the Coast

Guard's remote access technologies, Virtual Desktop Infrastructure (VDI; a VMWare product). The preliminary reports of this research were positive.

Inherently, different frequencies used in satellite communications have different characteristics. In general, lower frequencies also have lower bandwidth capacity (Minoli, 2015). This explains the lower throughput capacity of the Certus system, which leverages L-band signals. L-band is an Ultra High Frequency (UHF) that sits between 0.5 and 2 GHz (Newton, 2013). This is considered on the low end of the frequency spectrum when it comes to satellite communications. Despite its low bandwidth, L-band does have some benefits, especially when considering the maritime environment and its ability to propagate through water molecules in the earth's atmosphere. We expound upon some of these weather-related signal characteristics in the following sections.

The Coast Guard currently receives satellite communications signals in the Ku-band and utilizes L-band (Inmarsat FleetBroadband) as backup (Inmarsat, n.d.). The Ku-band is higher in frequencies (between 12 GHz and 18 GHz), and therefore is inherently capable of higher throughputs (Satmodo, 2019). With the Coast Guard's current satellite service provider, we are able to request more or less bandwidth allocation depending on the crew size and needs of a given class of ship. Although not directly discussed in our model, the ability to increase or decrease bandwidth allocations may be viewed as a strength by Coast Guard decision-makers and could impact the decision-making process.

For the purposes of this research, we assumed that a new PSC would require the same bandwidth as an NSC. Their crew complements and computer systems onboard will likely end up being comparable. So, an objective of 6 Mbps was identified. Any system capable of more bits per second would see diminishing returns in our model. The implications of these assumptions and methods for addressing them if they prove to be inaccurate are addressed in a later section.

2. Latency

One of the key components of broadband service is that it is partially subsidized by the government in order to bring internet connections to underserved populations. This has helped incentivize would-be satellite-based internet service providers to consider LEO and

MEO solutions (FCC, n.d.), and may ultimately benefit organizations such as the USCG in their search for more complete connectivity solutions. Historically, the USCG's large cutter fleet has maintained communications with Inmarsat satellites in geosynchronous orbit (GEO). An illustration of service areas from a GEO communications constellation is displayed in Figure 3.

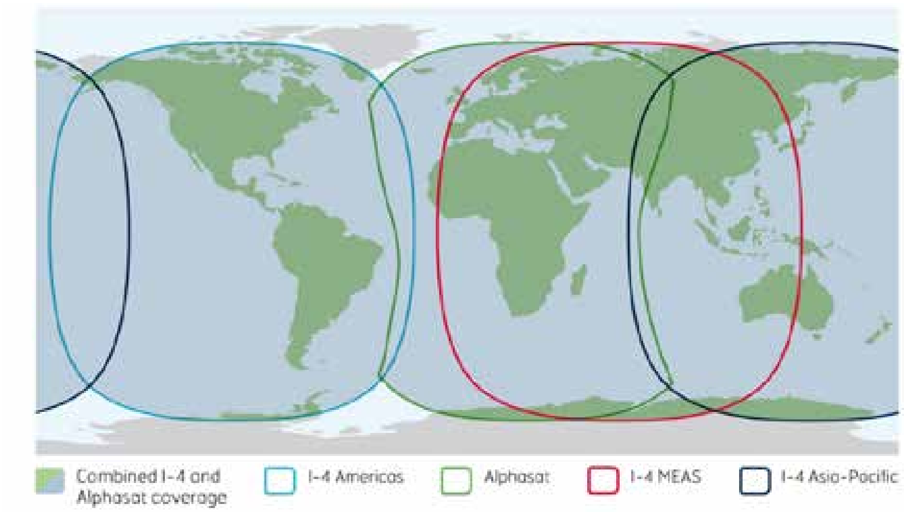

Figure 3. Inmarsat GEO Coverage.
Source: Inmarsat (n.d.).

While GEO satellites have been a primary means of marine communication for the last 40 years, they do not come without their drawbacks. The signal travel time for a GEO satellite system is between 500 and 1000 milliseconds (Ou, 2008). A major contributor to this extremely high latency is the vast distance to and from the earth that the signal needs to travel. This theoretical time combined with normal internet routing times, negatively impact web-based applications. The RDC's internet optimization study determined that round-trip latency for cutters utilizing GEO satellite systems averaged around 850 milliseconds (ms) and were observed as high as 4 seconds (or 4,000 ms). The low was approximately 500 ms. For the purposes of our analysis, we use the average of 850 ms in our model to establish a baseline for comparison of GEO constellations to different satellite technologies.

3. Signal Characteristics

In this section, we discuss some of the generalities for the effectiveness of a given SATCOM signal with regards to weather. It should be noted, that although certain signals are more susceptible to disruption from weather, there are satellite companies that employ a variety of technical solutions to overcome interruptions in service. Although other weather phenomena and atmospheric conditions exist that could have varying impacts on satellite connectivity, our research concentrates on the impacts of water in the atmosphere; namely, clouds, rain, and fog.

In general, "the higher the frequency, the higher the attenuation caused by rain fall. Moisture can degrade the link … [and in] heavy rain there could be portions of time when the link is unusable (outage)" (Minoli, 2015, p. 122). We found that Iridium Certus (the only fully operational 100% global LEO constellation to date) operates in the L-band frequency (Iridium, 2020). Due to its low frequency characteristics, this band should be a very effective system when it comes to weather, but as previously discussed in the bandwidth section, it is lacking in bandwidth availability.

4. Supportability

Supportability is used to describe the reliability and availability of a satellite system. Quite simply, this characteristic will measure the up-time of satellite connectivity throughout the year (outside of weather interference). Through the use of a service level agreement (SLA), a level of availability can be agreed upon ahead of signing up with a given satellite service provider (Gallaugher, 2019). In the event that a given service level is not achieved, there could be charge-backs built in to incentivize higher levels of performance by the vendor. These types of charge-backs are currently in place at the Coast Guard's TISCOM for other network service providers. Availability is critical to providing CGOne network access for day-to-day administration, as well as consistently achieving operational objectives. As historic data is developed for emerging satellite systems, these criteria can be used to differentiate between service providers.

C. FRAMEWORK

Within academia, there are several different frameworks used to aid organizations in decision-making. One of the more prominent frameworks in the DOD is cost–benefit analysis, or CBA (Candreva, 2017). The CBA attempts to express both the costs and the benefits of a program or several programs in monetary terms (Candreva, 2017). Once generated, the overall net benefit can then be compared between options to decide on the most beneficial course of action. One of the main issues with the CBA is that it is an analysis tool that requires a lot of rigor. Additionally, it can be very difficult to quantify the intangible costs and benefits associated with particular courses of action (Candreva, 2017). For our analysis, it would be very difficult to fully quantify the benefits received by the USCG in having reliable satellite connectivity. One would have to distill down how much more efficient the service is at conducting its missions in the Arctic and Antarctic regions and then somehow put a dollar figure on these efficiency gains. Additionally, Cellini and Kee (2015) highlighted the merits of a CBA when one is analyzing the benefits of a single policy or program to society. When multiple programs are involved, they recommend the use of a cost-effectiveness analysis, or CEA (Cellini & Kee, 2015).

A CEA is very similar to the CBA in that it also analyzes the costs of programs or policies. Where it differs is that instead of trying to fully quantify all the benefits of said program/policy, the model distills benefits into a measure of effectiveness (MOE) (Candreva, 2017). The analysis itself is relatively easy if the decision-maker is only concerned with optimizing one criteria or objective. For example, if car manufacturers were concerned only with maximizing speed, they would introduce technologies that furthered this end state without having to deal with other trade-offs. The inherent issue in this highly simplified example is that producers of cars and other major systems must deal with numerous constraints that ultimately affect the final design of a product. Car manufacturers must consider weight, fuel economy, cost, environmental constraints, safety, and passenger comfort as just a few of the various criteria. Multi-criteria decision-making, or MCDM, is one way of dealing with varying constraints. This methodology provides a path forward when dealing with multiple criteria, many of which are at odds

with each other (Ramaswami & Zionts, 2016). A variant of MCDM often applied to decision-making within the DOD is multi-objective decision-making, or MODM.

As outlined by Wall and MacKenzie (2015), most decision-making within the public sector involves solving decision problems with multiple objectives. They put forth a methodology that accounts for each of these objectives, along with their relative importance, to produce an overall MOE for each alternative being considered. Each step is reviewed in more detail with specific application to polar satellite connectivity later in this paper; however, an overarching summary can be found in Table 1.

Table 1. Steps in Multiple-objective Decision-Making. Adapted from Wall and MacKenzie (2015).

1	Develop a generic hierarchy or work breakdown structure for the system in question.
2	Develop a decision-maker preference within each objective/attribute in the form of a value function.
3	Develop importance or weights between the different objectives or attributes.
4	Sum the products of the respective weight and value for each objective or attribute to obtain the overall MOE for each alternative.
5	Perform sensitivity analysis to understand the impact of changing preferences.
6	Remove alternatives that were dominated by another.
7	Make the decision.

Wall and MacKenzie (2015) further outlined that this approach can yield five different types of solutions: superior, efficient, satisficing, marginal reasoning, and weighted cost. In some instances, a superior solution will exist, in that the alternative with the lowest cost will have the highest effectiveness. A sufficient solution (or solutions) is an alternative that is not dominated by or inferior to other alternatives. In the case of a satisficing solution, the alternative in question meets the minimum requirements and is under the maximum cost threshold. This requires the decision-maker to set bounds on the minimum acceptable effectiveness and maximum possible cost. The marginal reasoning alternative affords the decision-maker the ability to apply logic to the multiple efficient

solutions to arrive at an overarching selection. Finally, the weighted cost solution requires the analyst to derive a value function for cost as well as the other MOE (Wall & MacKenzie, 2015). Each of these types of solutions have their merits depending on application and constraints.

As previously discussed, various criteria are involved when choosing the best satellite connectivity option for polar assets. We have highlighted the importance of bandwidth, latency, signal characteristics, and resiliency. The supportability of the system is also a key attribute that stakeholders are interested in. Additionally, risk needs to be factored in as well. Dealing with multiple objectives to find the best satellite technology alternative lends itself to the application of MODM. Before applying the aforementioned model, it is important to explore some of the potential shortfalls of the model. Melese (2009), in the proceedings from the Sixth Annual Acquisition Research Symposium, highlighted that MCDM models, when applied during an analysis of alternatives (AoA), focus on life-cycle costs and system effectiveness. One of the major issues with this is that it only tangentially focuses on affordability by weighting cost as an evaluation criteria (Melese, 2009). This could potentially lead to cost overruns and many of the issues experienced in Acquisition Category 1D (ACAT1D) programs currently in the DOD portfolio. In response to this shortfall, Melese (2009) proposed a new model, known as the Economic Evaluation of Alternatives, or EEOA, that puts budget and affordability at the forefront of the acquisitions process. While there are a number of ways to implement this model, the choice mostly distills down to either fixing cost and choosing the option that can yield the maximum effectiveness for that cost, fixing the effectiveness and choosing the option that yields the lowest cost, or hybrid variants of the two (Melese, 2009). This approach requires upfront conversations with all offerors and ensures an affordable approach to acquisitions through collaboration with multiple contractors. While novel in approach, due to the fact that there is currently no program of record for obtaining polar satellite connectivity for the USCG, nor is there a budget allocated for a potential program, the implementation of this approach would not be feasible in our current discussion.

D. MODEL DEVELOPMENT

Drawing on Wall and MacKenzie's (2015) MODM methodology, the first task is to develop a hierarchy for polar satellite connectivity. The top level of concern in all defense acquisitions programs is the triple constraint: cost, schedule, and performance (DOD, 2015). In the MODM model, cost is treated as an independent variable, which leaves schedule and performance. There are two components of a system's performance: the characteristics or attributes that contribute to direct performance of the system's mission, and all the factors that relate to the system's ability to be supported. For a system providing satellite connectivity, the primary characteristics that contribute to its effectiveness are bandwidth, latency, signal characteristics, and resiliency. These have all been discussed at length previously in this chapter. From a supportability perspective, as with many DOD systems, it is important to explore the system's reliability, maintainability, and availability. Finally, it is also important to factor in program risk when discussing the viability of a particular alternative. In most cases, risk comes down to the overall maturity of the technology (DOD, 2015). This can be further distilled down into how mature the technology is toward accomplishing its goal and how mature the contractor's production process is for making the end item. A pictorial representation of the hierarchy can be seen in Figure 4.

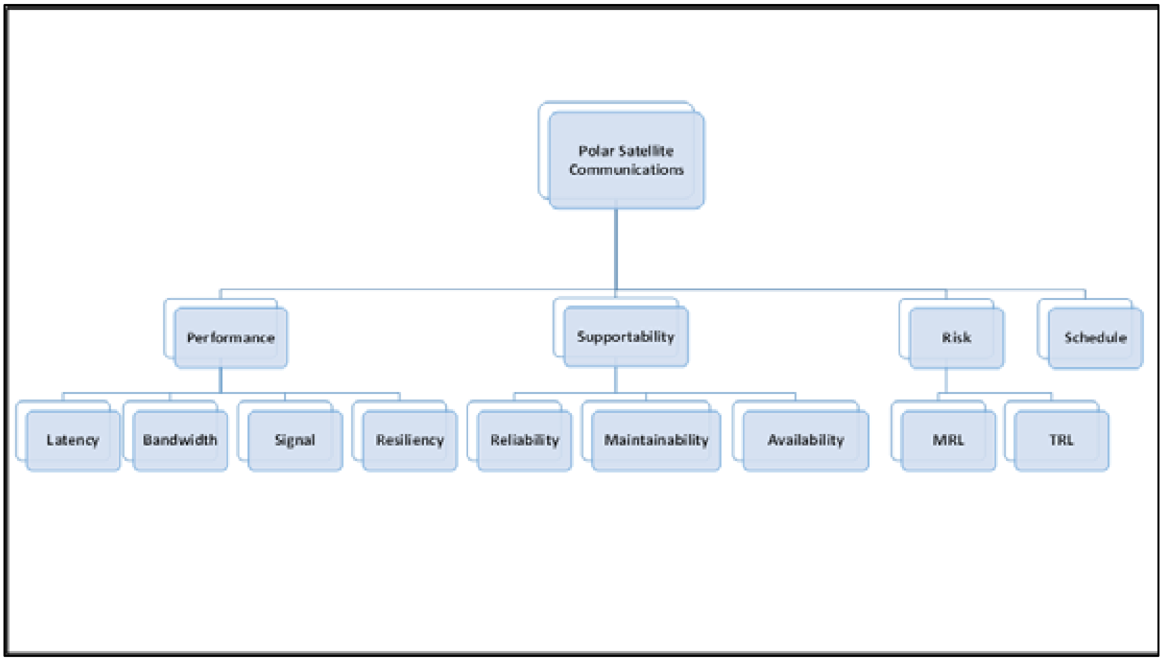

Figure 4. Initial Hierarchy for Polar SATCOM

In an ideal situation, Figure 4 would be the minimum hierarchy needed to assess the overarching MOE of a given polar satellite connectivity alternative. Wall and MacKenzie (2015), when outlining MODM, highlighted the fact that the hierarchy should be drilled down to the lowest quantifiable level. After researching public information on various LEO and MEO systems, as well as engaging subject matter experts within the USCG, we found that a few of the objectives were difficult to achieve this level of granularity. Under the maximizing performance objective, there is very little information on satellite system's resiliency. While it is of the utmost importance to ensure any satellite alternative for military applications is protected against the United States' adversaries, it is very difficult to quantify the metric. If the information does exist, it is most likely classified or proprietary, which is beyond the scope of this paper. Under the maximizing performance objective, it was also difficult to find any substantive information on the reliability and supportability of the satellite systems investigated. Additionally, while the software driving how the signals are transmitted and how the various satellites within a given constellation communicate may be modified from the ground, any physical maintenance to a satellite

would be difficult given current technological limitations. For the aforementioned reasons, it was decided that supportability should be analyzed at level 2 of the hierarchy.

Risk assessment and schedule also proved to be very difficult to assess with the desired level of detail. Outside of certain niche technologies, there are very few satellite communications systems that are mature enough to truly assess a technology readiness level. Additionally, without additional information, we have no way of understanding the manufacturing readiness level of a given manufacturer. Once again, because quantifying the level 3 objectives under risk is not possible given the current information, it is addressed more generally at level 2. Finally, while schedule is an important consideration for any program of record, it would be less paramount in a service-based acquisition. When a request for proposal would be released, the service would need to assess whether the current technology was acceptable or if they would be willing to wait for future technological maturity. Either way, the decision to move forward on acquiring the service would dictate the bidders and technology that could be leveraged. External to entering into a joint developmental effort with the DOD, the schedule piece would actually be a non-discriminating factor when acquiring the satellite service.

Considering the previous discussion, the discriminating performance factors are resiliency, latency, and bandwidth. Given the immaturity of LEO satellite communications, supportability must be analyzed at a higher level on the hierarchy as opposed to drilling down to the more detailed aspects of maintainability, reliability, and availability. Finally, while having MRLs and TRLs for various communications systems would be ideal, once again the immaturity of the technology relegates the risk analysis to level 2 of the hierarchy. Additionally, for a service-based acquisition, schedule is non-discriminating in nature and would not be used as part of the analysis. Taking these assumptions into account, a revised system hierarchy was developed and can be seen in Figure 5. This will be the basis for deriving the MODM model.

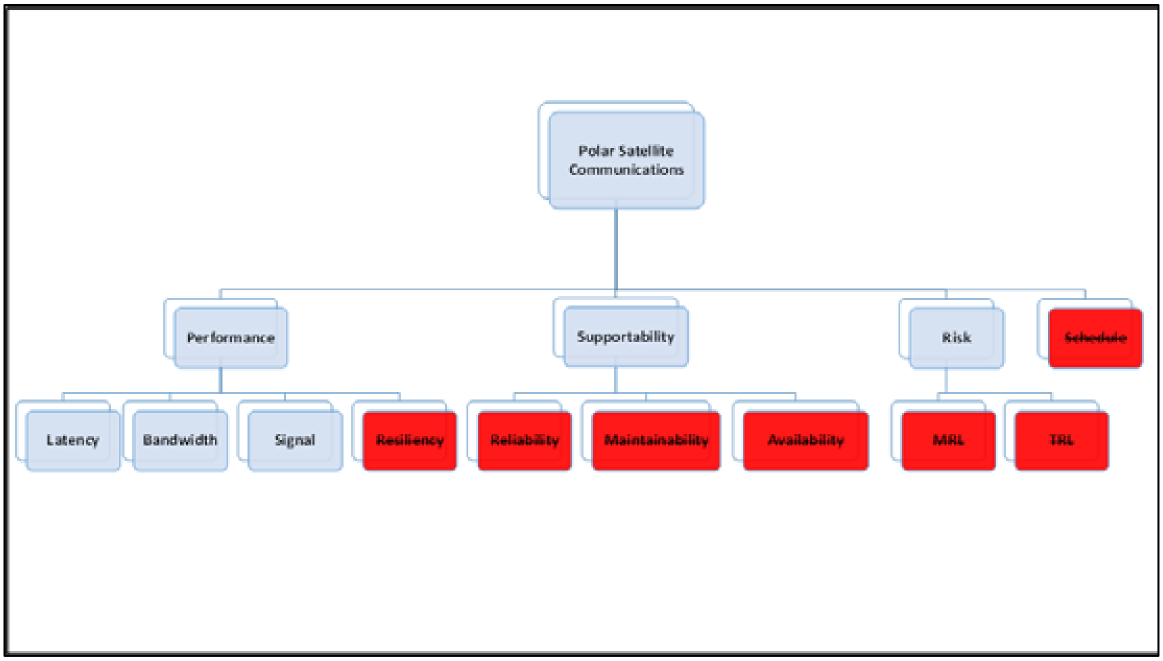

Figure 5. Revised Hierarchy for Polar SATCOM

E. VALUE FUNCTION GENERATION

As discussed by Wall and MacKenzie (2015), the value function is a way to differentiate alternatives within a given objective. One of the most efficient ways to develop the value functions would be to leverage the threshold and objective values as outlined in the PSC Capability Development Document (CDD) as lower and upper bounds and develop the functions from that baseline. We engaged the PSC program office to obtain this data; however, were only able to obtain the PSC Operational Requirements Document (ORD). Having stated that, the operational requirements document for the PSC was reviewed, and there is very little data to leverage because the goals are very operationally centric (USCG, 2015). We also obtained a requirements document generated by the operational arm of the Coast Guard specifically addressing objectives and thresholds for various USCG computer program usage times, a document currently being leveraged for the internet optimization initiative being conducted by the service (USCG, 2017). Unfortunately, this document formulated connectivity speed in the form of average time for executing various tasks across a myriad of service centric programs. For example, when executing a travel claim into the U.S.C.G's travel processing system, the time it takes is

largely dependent on the complexity of the travel claim (and its different files and their varying sizes) in addition to upload and download speeds. For this reason, this document could not be used to derive any objective or threshold criteria.

We decided to use current cutter performance speeds as threshold values and optimal satellite communication objectives as connectivity objectives for the value functions. The first value functions explored were underneath the maximizing performance threshold, specifically dealing with all level 3 objectives. The average latency currently experienced by USCG cutters leveraging GEO technology is 850 milliseconds (ms). While mostly theoretical in nature, LEO constellations could achieve a latency of 50 milliseconds or better when the systems are fully operational (Jewett, 2020). Therefore, 850 ms (the status quo) was used as the threshold value and 50 ms was set as the objective. A linear value function was derived under the assumption that anything faster than 50 ms would result in only a small level of gained effectiveness. This curve can be seen in Figure 6.

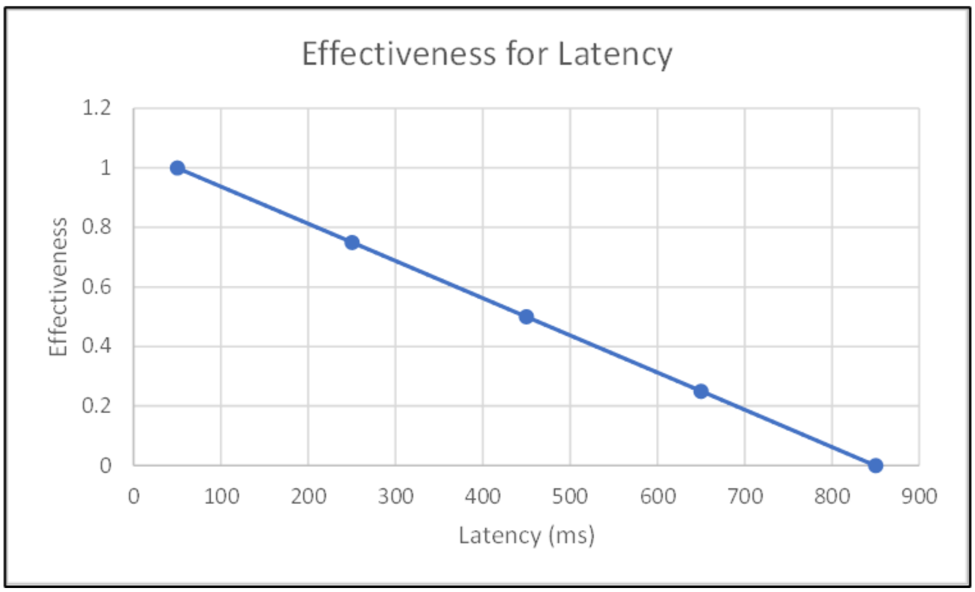

Figure 6. Value Function for Latency

For satellite bandwidth, it was previously determined that 4 Mbps was a suitable lower bound while greater than 6 Mbps would result in diminishing returns due to the current bandwidth usage in the fleet. Once again, the threshold value was assumed to be

not effective, while the objective value was assumed to be fully effective. Any additional bandwidth above 6 Mbps would not see any increase in effectiveness based off of the proposed value function. This relationship can be seen in Figure 7.

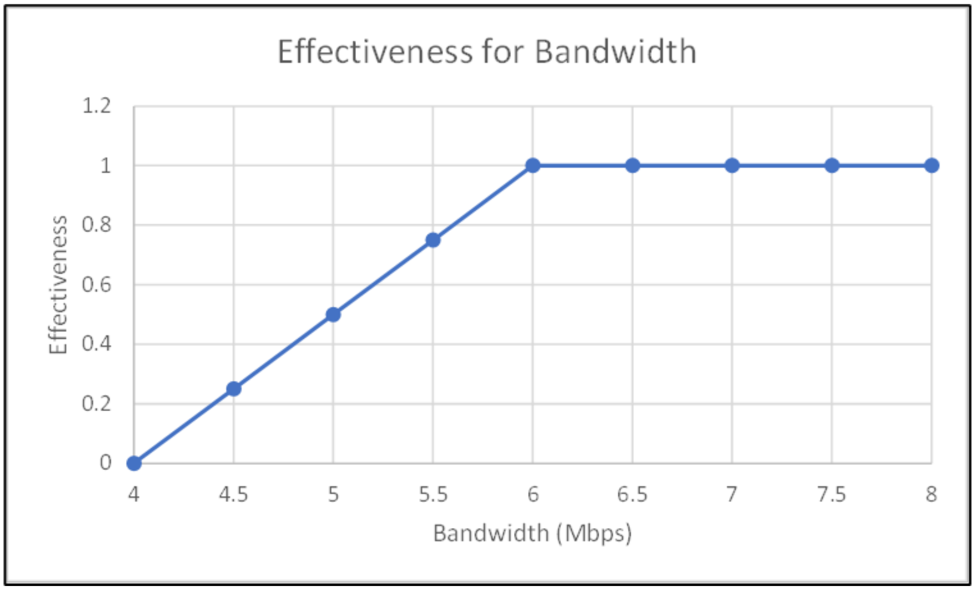

Figure 7. Value Function for Bandwidth

A value function for signal quality also must be derived. As previously discussed, the frequency of the signal makes it either more or less susceptible to effects of weather. Additionally, many communication satellites transmit across multiple signals, ensuring system redundancy and further protecting against weather or atmospheric interference (Minoli, 2015). Therefore, the rigor involved in deriving a value function across the spectrum of frequencies is beyond the scope of this paper. To simplify the model, while still ensuring order within the spectrum of signal frequencies, a stepwise function was developed. A value of 0 was assigned to communication frequencies above 18 GHz with no signal redundancy to account for weather interference. A value of .5 was assigned to frequencies below 18 GHz but above 4 GHz, or for systems with some level of dynamic signal allocation. Finally, a value of 1 was assigned for all signals 4 GHz or with advanced dynamic signal allocation across the electromagnetic spectrum.

The rationale for dealing with both supportability and risk was discussed previously in this section. Therefore, the value function for supportability was simplified to be 0 for a system with low supportability, .5 for a system with medium supportability, and 1.0 for a system with high supportability. To define what makes a satellite system on the low end of supportability, we decided to couple the metrics for reliability and availability. We deduced from Del Portillo et al.'s (2018) paper that the following up-time percentages would be reasonable from a communications network perspective. A satellite system is said to have low supportability if its mean time between failure (MTBF) is less than 3 years for a satellite and the system's up time is lower than 99%. A system is said to have a medium level of supportability if it has a MTBF between 3 and 7 years and an up time between 99% and 99.5%. Finally, a satellite system is considered highly supportable if its MTBF is greater than 7 years and its up time is greater than 99.5%. The same step function can be applied to risk to account for its importance while simplifying the model due to lack of data. A high-risk system would see an effectiveness score of 0, while a medium risk system would see an effectiveness score of .5. Finally, a low risk system would get an effectiveness score of 1. When the technology readiness level (TRL) and manufacturing readiness level (MRL) can be accurately obtained, these specific scores can become more granular, providing more validity to the model.

F. OBJECTIVE WEIGHTS

As previously stated, the program office was unable to provide an initial capabilities document (ICD) or CDD to help us better understand the importance of various objectives for the acquisition. Within a typical DOD acquisition, the CDD would not only provide the objective and threshold values of pertinent criteria, which would better inform the value functions, but it would also outline the key performance parameters (KPPs) and key system attributes (KSAs), which would identify the most important criteria involved in the acquisition (DOD, 2015). The ORD was also reviewed at length; however, it did little to provide any granularity into what SATCOM characteristics the user desired (USCG, 2015). A requirements document from the office of command, control, communications, computers, and intelligence (C4I) capabilities did not provide any further clarity (USCG, 2017). We hoped that the individual software operating requirements outlined as a basis

for the connectivity optimization project across all afloat platforms could be used to derive pertinent SATCOM requirements. Unfortunately, due to the metrics being somewhat arbitrary and varied based on software program, user, and task variance, this document proved to be of little value when distilling down user desires for SATCOM. The final, and most fruitful, activity was having a phone conversation with the government service (GS) employees at the USCG Research and Development Center (RDC), leading both the internet optimization study and the polar connectivity study for the Coast Guard.

In discussions with RDC staff, we determined that satellite performance was the most important criteria on the hierarchy (D. Cote, personal communication, September 1, 2020). The performance characteristics, (bandwidth, latency, and signal), were more than twice as important as supportability (D. Cote, personal communication, September 1, 2020). They specifically identified historical characteristics in GEO satellite technology citing lack of issues with reliability and availability of the signal despite having only four satellites in orbit. While not fully proven, a constellation of LEO satellites should meet or exceed the availability and reliability standards of the current GEO technology (D. Cote, personal communication, September 1, 2020). In addition to performance and supportability, risk must be factored into any acquisition decision (DOD, 2015). Right now, most of the viable polar SATCOM options are still fairly new technology. Taking that into consideration, even as the technology starts to reach viability, risk must be factored in to account for unknown characteristics in LEO constellations that are not fully deployed today. Additionally, not only does technical risk come into play, but manufacturing risk for new satellites must also be accounted for (DOD, 2015). Keeping all these factors in mind, we decided to weight the performance of the system at 0.70, the supportability of the system at 0.20, and finally the risk of the system at 0.10.

Performance was further broken down into latency, bandwidth, and signal quality. During our discussion, the RDC staff identified that initial studies of bandwidth usage across major cutter classes found that at peak utilization the most bandwidth consumed was roughly 80% of the amount allocated (D. Cote, personal communication, September 1, 2020). The major limiting factor for GEO satellite connectivity has been the latency associated with the technology. For this reason, we deduced that latency was twice as

important as bandwidth. While bandwidth and latency are the two most obvious characteristics from an end-user perspective, signal quality must also be accounted for. The time it takes a signal to make a round trip coupled with the amount of data sent may mean nothing should the link be disrupted. For these reasons, a weighting breakdown of 0.60 for latency, 0.25 for bandwidth, and 0.15 for signal quality were assigned to add granularity to the performance weighting. A visual representation of the weights overlaid on the system hierarchy can be found in Figure 8.

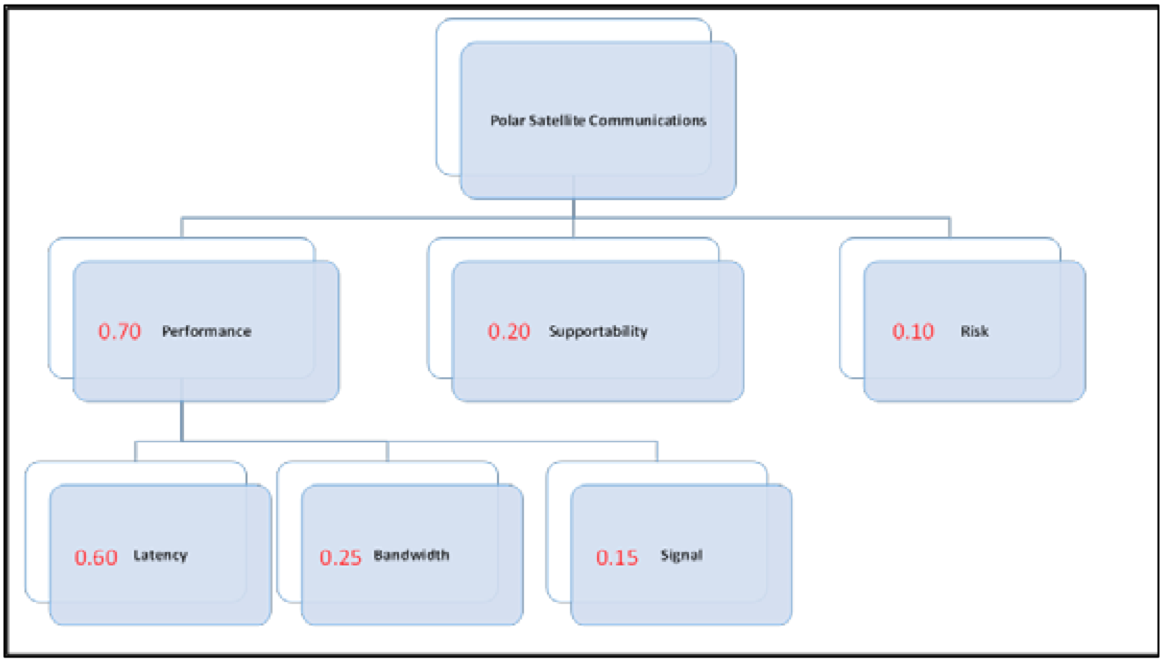

Figure 8. Simplified System Hierarchy with Assigned Weights

G. FINAL DECISION TOOL

In the previous paragraphs, we developed a hierarchy for the satellite communications systems. Value functions were derived to help sort between alternatives within each individual objective. Weights were then assigned (based off a USCG subject matter expert's assessment) to differentiate decision-maker preferences between the various categories of objective. The final stage is to combine this effort into one overarching equation to provide a means to calculate a MOE for each alternative. Wells

and MacKenzie (2015) portrayed this as a weighted sum of the value functions. The following equation was developed with the aforementioned process in mind.

$$MOE = 0.70 * \big((0.60 * x) + (0.25 * y) + (0.15 * z)\big) + 0.20 * A + 0.10 * B$$

where $x = -0.00125 * \alpha + 1.0625, (\alpha = latency\ of\ system\ in\ milliseconds)$

$$y = 0.5 * \beta - 2, (\beta = bandwidth\ of\ system\ in\ megabits\ per\ second)$$

$$z = \begin{pmatrix} 0\ if\ signal\ is\ poor \\ 0.5\ if\ signal\ is\ moderate \\ 1.0\ if\ signal\ is\ good \end{pmatrix}$$

$$A = \begin{pmatrix} 0\ if\ supportability\ is\ low \\ 0.5\ if\ supportability\ is\ medium \\ 1.0\ if\ supportability\ is\ high \end{pmatrix}$$

$$B = \begin{pmatrix} 0\ if\ risk\ is\ high \\ 0.5\ if\ risk\ is\ medium \\ 1.0\ if\ risk\ is\ low \end{pmatrix}$$

Once the alternatives are derived and the various independent variables are obtained, an MOE can be calculated and assigned to each alternative. Life-cycle costs will then have to be estimated, and finally each alternative's MOE and LCL must be plotted to compare the options available to the decision-maker. Additionally, sensitivity analysis will have to be conducted to truly understand the impact of changing the assigned weights on overall outcome. The last steps cannot be accomplished because of the immature nature of the technology and the lack of publicly available data for the top commercial companies. Some raw data was able to be obtained and will be used to at least illustrate how the model can be applied.

H. MODEL APPLICATION

Telesat, (one of the many LEO SATCOM companies), has conducted several tests with their prototype LEO system. Of note, they partnered with an antenna manufacturing company called C-COM and performed a test with publicly released data in February of

2020 (C-COM Satellite Systems, 2020). This data can be used to illustrate the application of the previously developed model. During this test, C-COM reported that it was able to achieve a bandwidth of 158 Mbps with a latency of less than 40 ms (C-COM Satellite Systems, 2020). Additionally, the signal that was used was Ka band. This data can be entered into the model to generate an associated MOE for this burgeoning technology.

The aforementioned values were entered into our model and yielded the following results:

$x = 1, because\ \alpha < 50ms$

$y = 1, because\ \beta > 6Mbps$

$z = (0, because\ Ka\ Band > 18Ghz)$

$A = (0.5, medium\ supportability\ is\ assumed)$

$B = (0.5, medium\ risk\ is\ assumed)$

$\text{MOE} = 0.70 * \big((0.60 * 1) + (0.25 * 1) + (0.15 * 0)\big) + 0.20 * 0.5 + 0.10 * 0.5$

$MOE = 0.745$

Telesat is one of the only companies currently providing public data from initial system tests of their LEO communications satellites. While they did advertise the signal quality, latency, and bandwidth, they did not address how mature the technology was nor did they communicate the level of supportability of the system. Medium supportability and risk were assumed to illustrate the applicability of the model.

When fully implemented, the above model will be applied to all bidders on a satellite communications contract for the USCG. The weights of the various categories would be adjusted to give the source selection team a better understanding of the sensitivity of the model and could be adjusted accordingly. Finally, life-cycle costs from each alternative should be plotted against the calculated MOEs to see if a superior solution exists (lowest cost for best performance). If there is no one superior solution, then the various efficient solutions will have to be compared against one another by the selection team to determine the preferred system.

Our research in this paper was generally relegated to deriving a model for determining the best available satellite communications system for the USCG's future polar fleet. That being said, the majority of the research explored MEO/LEO constellations and their advantages in the Arctic. In our future research section, we discuss alternative technologies that may also aid the Coast Guard in communicating in austere environments.

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IV. FUTURE RESEARCH

Although this paper has mainly focused on non-geosynchronous satellite communications solutions that may be available, we acknowledge that there could be other technologies available or in development that could potentially fill the Arctic communications gap. The following section covers different potential communications technologies and additional areas of related research that may prove useful to the USCG in identifying mission-enhancing technologies.

A. HIGH-ALTITUDE AEROSTATS

There are recent and on-going studies in the use of high-altitude balloons, also called “aerostats.” Aerostats have been used for different purposes throughout the DOD for decades. In a 2012 paper, a stratospheric balloon was utilized to help determine that Automatic Identification System (AIS) signals (used for navigation and tracking of commercial vessels), could be received by a constellation of small LEO satellites operating over the Arctic region (Larsen et al., 2012). Although AIS uses a relatively small amount of bandwidth compared to typical internet connections, similar studies could be done to determine the feasibility of providing shipboard connectivity in the Arctic. Many aerostats used by the DOD are tethered to the ground and used for Signals Intelligence (SIGINT) missions (Tenenbaum, 2016). Whether tethered or free-moving, stratospheric balloons may be able to relay shipboard communications to terrestrial or space-based communications networks.

B. COMMUNICATIONS DRONES

Projects that utilize drones to receive and relay communications traffic are also potential sources of future research. Facebook’s Aquila project (canceled in June 2018) had intended to launch a large solar powered drone into the stratosphere, which would have provided internet connectivity to large remote areas (Moore, 2018). A fleet of commercial or government-controlled drones could potentially provide connectivity in the remote polar regions, or act as a deployable back-up system in other areas of potential conflict. Further research is required to understand how communications drones could be leveraged, and

what capabilities they could provide that would improve communications or improve resiliency of communication systems. This technology would likely require significant development and a formal major acquisition process. Notionally, drones could provide a similar capability to the balloons mentioned in the previous section.

C. LEVERAGING NAVY SOLUTIONS

Although the DOD possesses satellites capable of providing connectivity links to the north pole, Coast Guard assets have not been granted access to these systems. The Enhanced Polar System (EPS), and its predecessor, the Interim Polar System (IPS) are capable of providing communications above 65 degrees north due to their highly inclined orbit (King & Riccio, 2010). Not just with regards to Arctic communications, there is a lack of integration across the board when it comes to utilization of DOD communications networks. Although the Coast Guard is not usually a part of "Big Navy" missions, this dynamic is changing. As a result, "the Coast Guard needs to redefine its role within the Navy's future fleet design to maintain relevance in its defense readiness mission area" (Allen, 2019). In the Arctic, the Middle East, the South China Sea, or beyond, "the real value Coast Guard cutters could provide to a DOD battle network is serving as maritime sensor nodes that can relay targeting data to the shooters" (Allen, 2019). The Coast Guard needs the ability to seamlessly integrate into operations with the Navy and the DOD at large. For that, standardized SATCOM systems between the Navy and the Coast Guard would be invaluable. It should be noted that even if a DOD solution is available to the Coast Guard from these HEO systems, due to the orbital characteristics of these satellites, they would not function in the Antarctica (M. Crook, personal communication, December 17, 2019), and there may not be a business case for the commercial launch of a HEO system that could service the southern hemisphere.

D. FEASIBILITY OF LAUNCHING NEW SATELLITE SYSTEM

The idea of the Coast Guard launching their own satellite constellation into orbit to facilitate communications may have once been laughable. The commercialization of space and the appearance of small satellites in the field of research may have changed that. These small (and relatively inexpensive) satellites are often referred to as CubeSats or SmallSats

(Valinia et al., 2019). In fact, the Coast Guard recently deployed two CubeSats, controlled by two ground stations (one at the Coast Guard Academy in New London, Connecticut, and the other in Fairbanks, Alaska) to explore the feasibility of space-based sensors in Arctic search-and-rescue (DiRenzo & Boyd, 2019). Deploying a specialized constellation of communications CubeSats, useable in the Arctic and Antarctic, could be a potential solution set. However, determining the cost, the management overhead, and the technical feasibility of such an undertaking was outside of the scope of this project.

E. SOFTWARE-DEFINED SATELLITE MODEM

A traditional modem is a "purpose-built piece of hardware consisting of discrete components, logic devices, and low-level programming language to provide the directives for the hardware to accomplish the steps required to create the final waveform to be transmitted" (Beeler & Toyserkani, 2019). A software designed modem could identify what type of signal is being received, seamlessly adapt its internal coding to select the applicable demodulation, and process the signal appropriately. This may have huge implications for the future of warfare. "One of the widely known principles of the Chinese People's Liberation Army anti-access, area-denial (A2/AD) strategy is to impede U.S. freedom of action by targeting space capabilities" (Bell & Rogers, 2014, p. 143). A "smart" terminal, potentially with artificial intelligence (AI) capabilities built-in (for the purposes of countering adversaries counter-satellite and jamming activities) would be a game changer in a contested, degraded, and operationally limited (CDO) environment.

A "smart" terminal (that provides the resiliency the Navy and the DOD at large are striving for) could be accomplished with a software defined satellite modem. This type of modem could greatly improve the flexibility of the USCG's current communication networks, providing the "terminal and network agility" called for in the Space Force's SATCOM vision (U.S. Space Force, 2020, p. 1). There are drastic differences in the type of services different satellite systems can provide. The types of satellites used across the Department of Defense and by the U.S. government in general are very diverse. Each of these separate service providers, either military or commercial, designs their system with very specific needs in mind. Some are older legacy systems with limited throughput.

Others, like state-of-the-art satellite constellations such as Mobile User Objective System (MUOS), provide total global coverage and increased throughput capabilities (Department of the Navy, 2012). In the past, the Coast Guard has not benefitted from this plethora of satellite systems. As one cutterman pointed out, “The Coast Guard [onboard a given vessel] has only one satellite channel available to run both secret internet protocol router (SIPR) and non-classified internet protocol router (NIPR) nets [while] the Navy uses several, across multiple frequency ranges, and at much higher transmission rates” (Allen, 2019). As this excerpt states, the DOD utilizes many different SATCOM systems depending on the mission, availability, and needs of the end-users. These different systems utilize different waveforms (ways that a signal is encoded), bands (electromagnetic frequencies), and orbits (or the altitude and path a satellite or group of satellites takes around the earth).

The Coast Guard may be able to best leverage these emerging commercial products by allowing different satellites with multi-waveform, multi-band, and multi-orbit characteristics to be utilized across their fleets (J. Shaw, personal communication, February 21, 2020). This will better enable the resiliency and flexibility that a modern global warfighting power demands. Allowing a single terminal to make use of a broad swath of available satellite systems gives an end-user the greatest chance for avoiding interruption in service, while enabling a commander the flexibility to choose a higher bandwidth connection in carrying out a given mission. Thousands of new commercial satellites are being planned for launch in the coming years, such as Boeing’s O3b mPOWER (a MEO constellation consisting of eleven satellites; Boeing, 2020). LeoSat and Telesat have plans to build out their LEO constellations in the coming years as well (LeoSat, n.d.; Telesat, n.d.). SpaceX alone plans to launch as many as 12,000 satellites for their StarLink system (Thompson, 2020). These satellites represent a huge uptick in available communications channels that could potentially be used by the U.S. government as well as the military and could be fully leveraged through the use of a software defined modem. Furthermore, a software defined modem could allow for both forward and backward compatibility, and not keep an organization beholden to a single satellite service provider. This approach will help to future-proof the next generation of satellite terminal technology (J. Shaw, personal communication, February 21, 2020), while simultaneously promoting competition and

innovation among the COMSATCOM industry. By inserting the type of flexibility that a software-defined modem allows, our SATCOM systems are better prepared for future technological advances, while simultaneously giving today's end-user the resiliency they need to execute their missions.

As outlined in previous chapters, the U.S. Coast Guard will undoubtedly see increased activity in the Arctic region, making reliable communications increasingly important. A flexible communications system that utilizes government and commercial access for voice and data transmission will be vital to the protection of life and property, and the management of these expanding areas of navigable waters. The ability to use multiple types of orbits could result in the ability of military ships transiting above 70 degrees north latitude to continue to connect to their respective networks utilizing the HEO characteristics of the IPS and EPS systems. That does not solve the connectivity in the Antarctic, as the current HEO satellite systems are mainly useful over the north pole. But a software defined system could also make use of upcoming LEO and MEO satellite constellations that would be useable around the globe, to include the Antarctic. This type of flexibility and future-proofing could greatly benefit the Coast Guard, the Navy, and potentially the DOD as a whole (J. Shaw, personal communication, February 21, 2020).

Theoretically, software defined modems would be capable of providing a self-healing connection to government networks that could be completely transparent to the end-user. Likewise, voice communications over satellite could also be seamlessly transitioned from one system to another based on the current threat environment. These capabilities alone would provide much of the redundancy, flexibility, and agility that the Space Force and the rest of the DOD is looking for in order to overcome the threats that potential adversaries pose (both today and into the future). The Coast Guard, as a player in modern day geopolitical theaters, would also benefit from being included in such an acquisition.

The Space Force outlines acquisitions goals in their vision for satellite communications. The main objective here is to avoid "stovepipes of the past" created by disparate commands and services acquiring satellite systems separate from one another (U.S. Space Force, 2020, p. 6). This will bring all (or at the very least, a majority) of these

SATCOM services (operated both commercially and by the military) under the management of the Space Force in order to create “a single entry point for all SATCOM requirements” (U.S. Space Force, 2020, p. 6). This will certainly help clear up some confusion about how to integrate with different SATCOM systems (especially for a non-DOD agency such as the Coast Guard), but the implications of the Space Force’s vision does not totally address how shipboard satellite terminal equipment is to be acquired. Therefore, the Coast Guard will need to develop the best path forward. If the Coast Guard works in partnerships with the Navy on a software-defined modem, they may need to look at newly published updates to DODI 5000.02 for the Adaptive Acquisition Framework (AAF) and how to approach software acquisitions.

V. CONCLUSION

The Coast Guard's increasing role in the Arctic has been solidified through Congress's funding commitment to the Polar Security Cutter program. It has been more than 50 years since the last heavy icebreaker was built on U.S. soil. However, although several technical advancements have occurred over the years, a substantial capability gap still exists with regard to internet connectivity. Our current world has become increasingly reliant on various internet tools to conduct daily business. The USCG is no different. The current marine communications leveraged by the service are provided by a GEO SATCOM service. As discussed in the previous pages, GEO SATCOM cannot be used in polar regions because of their equatorial orbit which creates "blind spots" north of 81 degrees latitude in the northern hemisphere and south of 81 degrees latitude in the southern hemisphere (Bekkadal, 2014). New technologies must be leveraged to ensure optimal mission capability for the USCG's future polar assets.

It was important to understand the attributes associated with SATCOM technology prior to researching emerging technology. Initial research uncovered that latency, bandwidth, and signal quality were all important performance characteristics of SATCOM (Newton, 2013). To further understand the USCG's perspective on SATCOM, members of the RDC SATCOM/WAN acceleration-optimization technology assessment team were consulted. While all performance characteristics were explored, it was determined that latency was the limiting factor for current USCG assets and would also impact the new polar assets as well (D. Cote, personal communication, September 1, 2020). After understanding performance requirements for optimal Arctic SATCOM, current and future technologies were canvased. While GEO is the predominant SATCOM leveraged throughout the world, newly immerging MEO and LEO constellations will quickly surpass this capability, simultaneously overcoming some of the shortfalls related to Arctic communication (due to their non-equatorial orbits; Patterson, 2015). Of particular note, LEO communications solutions, and the potential for use onboard Coast Guard cutters, have been discussed since the early 2000s (Campen & Clark, 2002), the speed at which these technologies are being deployed in recent months and years suggests they will be a

viable solution soon. Unfortunately, due to the infancy of the technology, few systems can currently be leveraged. For this reason, it was decided to develop a decision model for choosing a future communications solution.

The CBA is common within the business world for driving decisions. This methodology, however, requires a substantial amount of rigor. Additionally, each cost and benefit must be monetized to understand the true benefit of each course of action (Candreva, 2017). As the USCG has not fully developed all criteria for their communications need, this approach was ruled out. Out of the additional decision methodologies explored, MODM fit the problem set best. This approach combined service-specific criteria weighting, a system hierarchy, and value functions to help striate various COAs. These separate items could be combined to develop a single MOE for each COA (Wall & Mackenzie, 2015). These MOEs could then be plotted against life-cycle cost estimates to help a source selection board choose the best communications service. External to the performance characteristics previously mentioned, additional characteristics had to be determined to allow for comparison of future COAs.

The supportability component of SATCOM was the next area explored. While reliability, availability, and maintainability are all vital components of a system's supportability, detailed data on burgeoning LEO technology was difficult to find (DOD, 2015). Eventually it was decided to decrease the granularity and deal with supportability as a factor in and of itself. Additionally, a generalized framework was formulated for risk. As the service priorities mature along with the technology, additional granularity is expected in both areas of analysis. Finally, schedule was reviewed as a potential factor; however, because the acquisition would most likely be service-based, it was determined that schedule would be non-discriminating. The outcome of this research resulted in the first formulation of an MOE calculator to be used by future source selection groups to determine the best way ahead for Arctic communications. Additionally, this model could also be adapted, should the USCG look to move in a different direction regarding all cutter communications.

Finally, there were several areas of future research uncovered, but not fully explored by this paper. First were the known SATCOM communications options. Aerostats

and UAS technologies do exist that can provide communications signals to be leveraged in austere environments. Further exploration into this area could yield positive results. Additionally, the research was relegated to commercial SATCOM options. MILSATCOM, run by various entities within the DOD, could be another avenue for the USCG to explore. While initially scoped to be part of the research, it was decided to stay away from this particular area of study due to the classification associated with most MILSATCOM information. Finally, research potential exists for shipboard SATCOM equipment, such as software defined modems, which the USCG could potentially benefit from leveraging DOD innovations in SATCOM services while simultaneously protecting communications from disruption by U.S. adversaries.

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